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# Thin-Walled Compliant Plastic Structures for Meso-Scale Fluidic Systems

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# Thin-walled compliant plastic structures for meso-scale fluidic systems

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## ABSTRACT

Thin-walled, compliant plastic structures for meso-scale fluidic systems were fabricated, tested and used to demonstrate valving, pumping, metering and mixing. These structures permit the isolation of actuators and sensors from the working fluid, thereby reducing chemical compatibility issues. The thin-walled, compliant plastic structures can be used in either a permanent, reusable system or as an inexpensive disposable for single-use assay systems. The implementation of valving, pumping, mixing and metering operations involve only an elastic change in the mechanical shape of various portions of the structure. Advantages provided by the thin-walled plastic structures include reduced dead volume and rapid mixing. Five different methods for fabricating the thin-walled plastic structures discussed including laser welding, molding, vacuum forming, thermal heat staking and photolithographic patterning techniques.

Keywords: microfluidics, plastics, micropump, microvalve, micromixer, microfabrication.

## 1. INTRODUCTION

The use of microfluidic devices for medical and pharmaceutical applications has been proliferating in both research and in products of small companies. Research focus has shifted in the past several years from component technology to systems technology. Microfluidic systems appear to offer distinct advantages over conventional systems in terms of reduced sample size and reagent use as well as lower manufacturing and material costs. The early MEMS efforts in fluidic devices typically utilized etched silicon and glass as did other MEMS devices such as pressure sensors and accelerometers. There is significant interest, however, in low-cost plastics for biological applications because the biological testing industry is oriented toward disposable plastics to prevent cross-contamination between tests.

Most plastic fluidic systems use devices with structure and dimensions similar to those designed for fabrication in silicon. In these silicon-derived systems, many valves feature flexible membranes which seat against a rigid wall and many pumps vibrate a membrane against fluids constrained by rigid walls. In this paper an alternative approach is described in which a completely flexible, thin-wall, compliant plastic fluidic system is used. Two thin sheets of plastic can be formed and bonded to fabricate a monolithic system of fluidic tubes and plenums as depicted in Figure 1. The structure is completely compliant and does not have a rigid substrate or other stiffening structure. External pressure is used to collapse the internal cavities of the plastic structure in order to provide valving, pumping, metering and mixing functions. Accordingly, the valves are now designed as pinch valves, the pumps are now designed to be peristaltic in nature, the mixers are now designed such that external actuators "knead" alternate parts of the fluid contained within a single plenum, and the metering components are designed as collapsible reservoirs. The use of a thin-walled, compliant plastic structures allows the sample fluid to be completely isolated from actuators which may not be compatible with fluid contact. For example, thin-walled, compliant plastic structures make possible the use of thermal actuators which often require careful thermal management to reduce power consumption and response time. In addition to external actuation, it is possible that future systems can incorporate external optical sensing such that the sensing mechanism will also be isolated from the working fluid. Overall dead volume of the system may be reduced with the elimination of sharp-walled features commonly found in rigid-walled systems. Various techniques for fabricating a complete microfluidic system that functions as a "plastic insert" in a larger system are described. Some actuation methods that demonstrate typical fluidic operations such and valving, pumping, mixing and metering of fluids are presented.

## DISCUSSION

A typical thin-walled compliant plastic structure built for a biological assay is shown in Figure 1. The functions of the system are to meter two aliquots of liquid, to pump them into a mixing chamber, to mix the liquids and finally to pump the

solution to a sensor. The fluidic circuit is formed using two thin (50-100 μm) sheets of plastic (polyethylene, polypropylene, or silicone) which have been bonded together in an intricate manner so as to define the internal plenums and interconnecting tubes. A formed plastic part made from laser-welded polypropylene is shown in Figure 2. Since the entire structure is flexible, the topology of various regions of the monolithic plastic structure (which are designated to be valving, pumping, mixing or metering regions) can altered by the application of an external force. Valving of the fluid within the internal tubes can be accomplished by externally pinching the tubes shut. Pumping can be accomplished by depressing a filled plenum to evacuate it. Metering consists of first venting a plenum region by externally compressing it to remove the air, then valving off exits while opening the inlet to draw in liquid. Mixing is achieved by alternately pressing against opposing portions of liquid in a plenum in a kneading type of motion using external actuators. Valving and pumping action are depicted in Figure 3. In this figure is shown a plenum (square section) with integral input and output tubes formed as a thin-walled, monolithic internal cavity by heatstaking two sheets of metallocene plastic. In Figure 3a, fluid is shown flowing through the plenum from the input tube to the output tube. External pneumatically-actuated, silicone-membrane actuator valves are placed against the input and the output tube walls. In Figure 3b the valve across the input tube is shown being actuated (closed) to stop fluid flowing into the plenum. The silicone membrane valve is pneumatically deflected upward, pinching the input tube against a clear coverplate, arresting fluid flow through the tube. Similarly, the fluid in the plenum can be evacuated through the output tube using a larger external pneumatically-actuated, silicone-membrane actuator placed against the plenum wall and actuated as shown in Figure 3c. Again, the silicone membrane is pneumatically deflected upward compressing the compliant plastic plenum against a clear coverplate and forcing the fluid out of the plenum via the open output tube. The amount of fluid evacuated from the plenum is defined by the volume displaced by the actuator and is accurate to within ±5%. External actuators can also be used to mix fluid contained in a plenum. In Figure 4 is shown a plenum in which pairs of externally actuated, silicone membrane actuators placed against the plenum wall are used to mix the liquid residing in a plenum. The pneumatically-actuated, silicone membrane actuators compress sections of the compliant plastic structure against a clear coverplate. The fluid is squeezed from this part of the plenum and is forced to merge with the fluid in other parts of the plenum. By alternating the operation of the actuators, mixing has been achieved within a few actuation cycles.

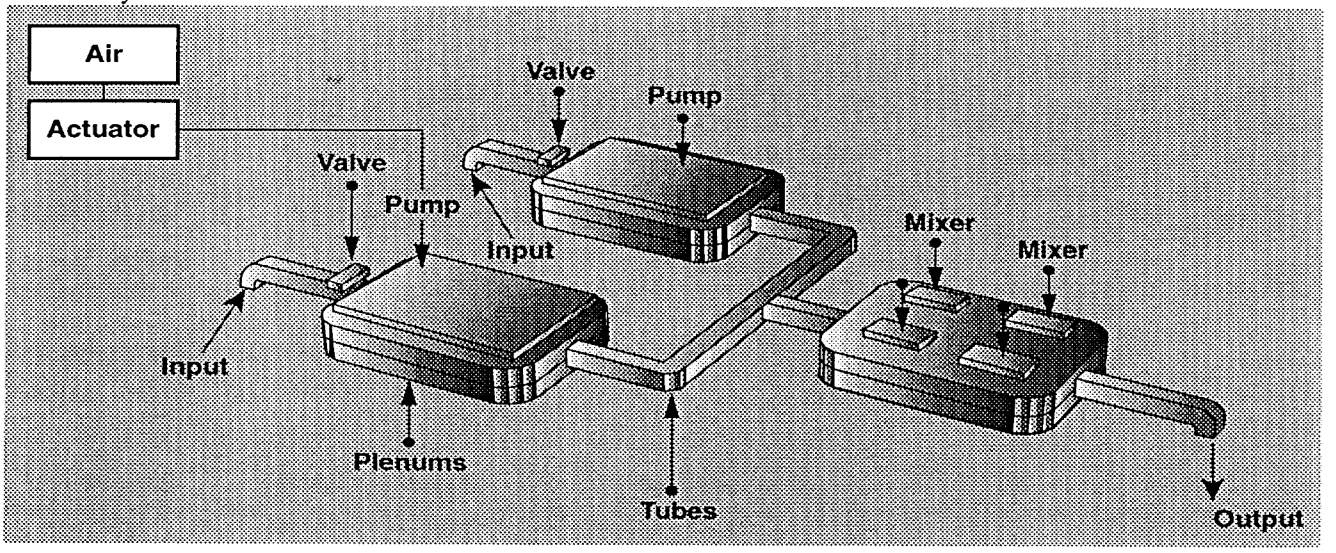


Figure 1. Schematic of a fluidic system fabricated using thin sheets of plastic. Two aliquots of liquid are metered into the pumping plenums. The fluid is pumped into the mixing section then pumped out to an external sensor. Valving, pumping, metering and mixing functions are provided by applying external pressure to the device which compresses the structure, transmitting forces to the fluid.

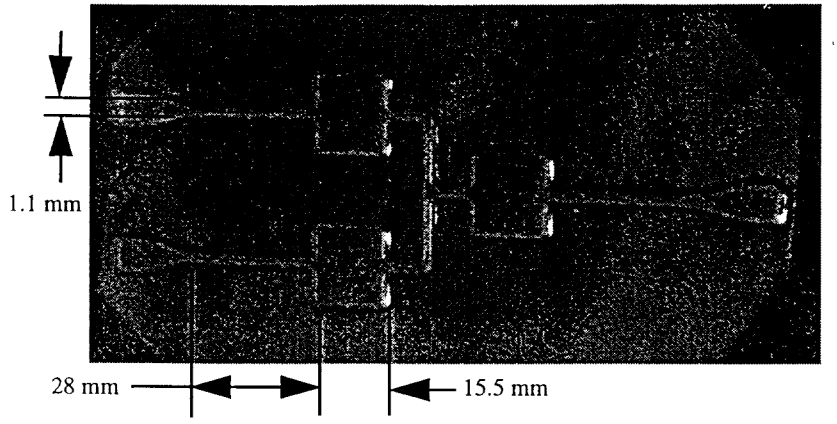


Figure 2. Two sheets of 50 μm thick polypropylene embossed and laser welded into a monolithic fluidic structure.

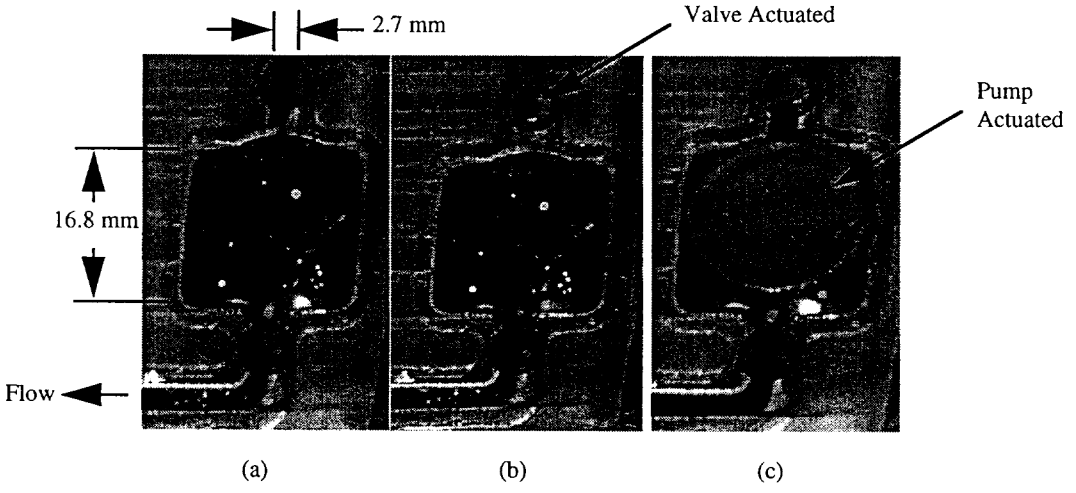


Figure 3. Fluid in plastic structure manipulated using external pneumatic actuators. (a) Normal flow (i.e. open valves). (b) Inlet valve closed. (c) Pumping actuation to 85% volume.

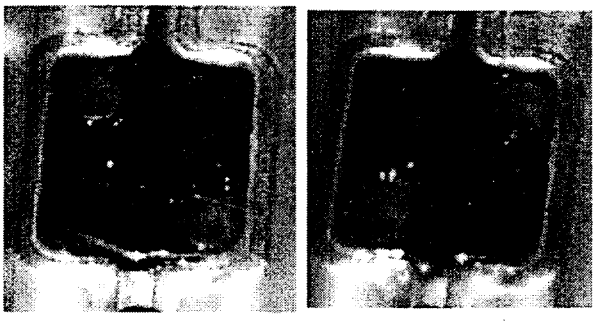

Figure 4. Actuators moved in opposed pairs can provide for mixing of the fluid in the plenum.

Thin-walled, compliant plastic systems designed to deliver 100-1000 μl volumes of fluid to a flow cytometer were designed, built and tested. Typical dimensions for the systems were flow channels 2.7 mm wide and roughly 3.5 cm in length with 16.8 mm square plenums. The gap between the plastic sheets varied from zero to 400 μm depending on the material and manufacturing technology as discussed in the fabrication section of this paper. Although fluid resistances varied from system to system depending on the complexity of the design, a typical pressure loss through the thin-walled, compliant plastic system was on the order of 20 - 34 kPa (3-5 psi). A flat metallocene (elastomeric LDPE) structure was used to meter a 1.16 ml aliquot of fluid to an accuracy of ±5%. The metering technique used was to inflate an unconstrained plenum at 34 kPa until the structure pinched off the input and exit tubes. Evacuation of this aliquot of liquid was achieved in less that 1 second using 275 kPa (40 psi) pressure in the external pneumatic actuators.

## FABRICATION

There are many different materials and fabrication methods that may be employed to make thin-walled, compliant plastic structures. The devices described in this paper were fabricated using polypropylene, polyethylene, silicone and metallocene. It was found that stiff plastics like polyethylene or polypropylene required pre-embossed structures to form plenums and tubing with sufficient cross-sectional area to avoid high flow resistances. It was relatively easy to emboss 50 μm polypropylene and polyethylene sheets to a depth of 200 μm with no distortion of the structure. Areas for valving should remain unembossed with zero gap between the halves of the plastic tubing to produce a good valve seal. The exception to this is molded silicone structures where gaps up to 180 μm across a 2.5 mm wide channel may be valved closed for a liquid operating at 34 kPa (5 psi). Elastomers are in some ways more attractive than stiff materials for use in these systems because they can be formed flat. These structures can be distorted to hold hundreds of microliters of fluid then can be flattened to near zero internal volume during valving and pumping operations. Care should still be exercised to design structures which conform well to streamlines to minimize trapped fluid. Both silicone and metallocene have been used for the thin-walled, compliant plastic structures.

Fabrication of the plastic inserts can be accomplished using any of several different methods. Five methods are described in this paper including laser welding, photolithographic definition, heat staking, vacuum forming using silicon molds and molding using silicon molds. The choice of fabrication method depends upon the material used, accuracy required and cost.

Laser welding of 50 μm thick polypropylene sheets was accomplished using a pulsed $CO_2$ laser that was slightly defocused to reduce power density. One half of the polypropylene structure was first embossed using a standard press operated at 700 kPa and 250°C. The plastic sheet was pressed into an aluminum mold which defined a pattern with a depth of 200 μm and linear dimensions between 1.3 mm and 15 mm. The embossed sheet was mated with a smaller-sized flat sheet and the two held together against a vacuum surface for intimate contact during the welding process. The laser energy used was approximately 3.3 W with a feed rate of 1.30 m/sec and a duty cycle of 25%. The weld line width was about 500 μm. Corners were rounded to a minimum radius of 130 μm to prevent the numerical translation stage from lagging in certain areas of the pattern and causing overheating of the plastic. These structures withstood internal pressures to 101 kPa (15 psi).

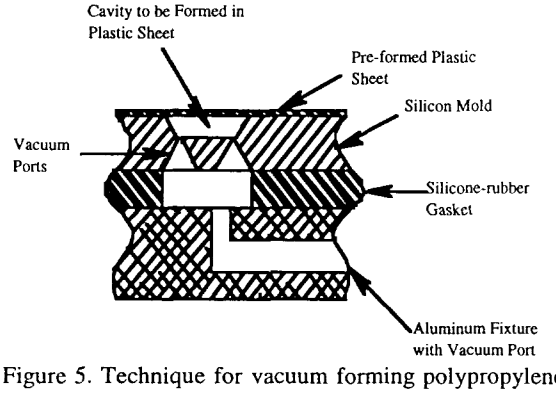


Figure 5. Technique for vacuum forming polypropylene structures.

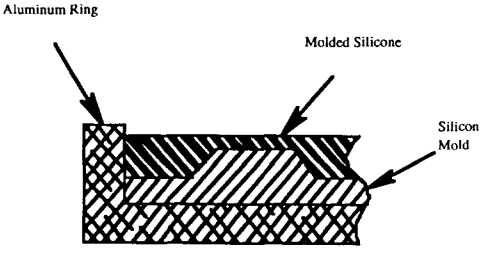


Figure 6. Technique for molding silicon structures.

Thin-walled plastic structures were also fabricated out of polypropylene sheets by vacuum forming into silicon molds as shown in Figure 5. Cavities corresponding to the external dimensions of the structure were etched in 400 μm thick silicon wafers using standard photolithographic patterning and etching techniques[2]. Vacuum vent holes were etched in from the backside of the wafer such that the openings in the front cavities were 100 μm in size. A silicone gasket was laser cut and placed used against a fixture to provide an interface between the silicon wafer mold and a vacuum pump. Two plastic sheets were placed between two mirrored imaged silicon vacuum molds. The entire structure was placed in an oven and the temperature raised to the glass transition temperature for about 15 minutes in a slow ramp up and down over a period of about 2 hours. The plastic faithfully conformed to the molded silicon and the two sheets fused to one another in areas that remained in contact throughout the oven baking process.

Thin-walled silicone structures were made using molding techniques as shown in Figure 6. Molds for silicone structures were made using standard silicon patterning and etching techniques to produce a negative of one half of the final molded plastic structure. The etched silicon wafer was placed in a metal ring which conformed to the circular outer diameter of the wafer. Two part the liquid silicone (Sylgard 184 - Dow Corning) was poured into the silicon/metal ring mold. Following a vacuum purge of the poured Sylgard 184 silicone for 30 minutes at 100 Torr pressure, it

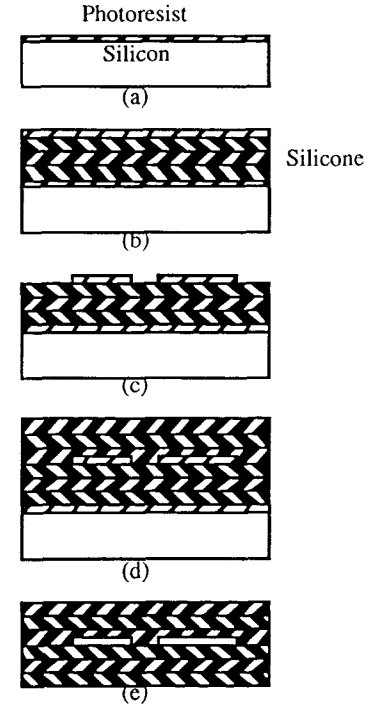


Figure 7. Process for spincoated silicone structures (a) wafer with photoresist (b) spin and cure three layers of silicone, spin on photoresist (c) photolithographically pattern photoresist (d) spin on and cure three additional layers of silicone (e) remove sacrificial photoresist in acetone.

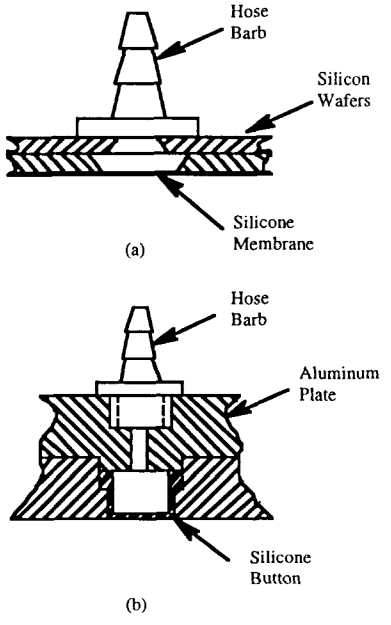


Figure 8. Methods for making silicone membrane pneumatic actuators (a) silicon wafer etching (b) conventional machining

was cured at 120°C for 15-20 minutes. To form the completed thin-walled, compliant plastic device, two mirrored molded devices were bonded together by painting additional silicone on the mating surfaces and heat curing the assembly. PEEK tubing was used to connect the molded monolithic structure to other devices supplying fluid to the thin-walled structure. The PEEK tubing was inserted into the molded channels and "glued" into place using the same Sylgard 184 silicone. Parts as small as 200 μm deep by 250 μm wide and up to 25 mm wide were molded in this manner.

Using a fourth approach, a virtually zero dead volume silicone thin-walled plastic structure was fabricated using a photolithographic definition process. The process flow is depicted in Figure 7. Silicone (Sylgard 184 - Dow Corning) was spun on a dummy wafer at 1000 rpm for 50 seconds. The dummy wafer can be silicon or glass coated with photoresist for easy removal of the structure. The silicone was cured at 120°C for 5 min. Three layers of silicone were applied. Photoresist was then applied and softbaked at 90°C for 20 min. The photoresist is patterned using standard UV photolithographic techniques[2] such that non-bonded areas were protected by photoresist. The silicone was oven dried at 120°C for 15 minutes then cleaned using oxygen plasma at 120 W for 2 minutes. Three additional layers of silicone were applied (spun on) over the photoresist using a 5 minute oven-cure for each layer. The final structure was cured for at least an additional 30 minutes. The entire structure was soaked in acetone to soften the resist which is then removed by flushing with acetone. The result was a very flat structure with internal cavities defined by the unbonded regions left by the sacrificial photoresist. The entire thickness of the silicone structure was 530 μm with linear channel widths of 1.2 mm. Smaller channel widths require thinner material to maintain overall structural flexibility. Occasionally, Sylgard 186 was brushed on the center layers to aid adhesion. Sylgard 186 was not found to be amenable to spin coating.

As a fifth approach, heat staking was used to form metallocene parts. This was perhaps the crudest but most economical of the methods for fabricating thin-walled plastic structures. Tooling was built such that areas to be welded were raised. Two flat sheets are pressed at temperature and pressure to form the part. The line width of the fused areas is about 1.7 mm. The heat staked bonds held to internal pressures of 70 kPa (10 psi) internal pressures.

Laser welding can accommodate design changes quickly with no additional tooling costs. Laser welding also allows for thin bond lines and thus more tightly packed feature designs than heat staking, for example. The plastic sheets must be held in intimate contact, however, which is difficult when the plastic sheets are pre-embossed. Also, the previously mentioned CO2 laser was designed for metal cutting and consequently, control at the low energies needed for plastic welding was difficult. Vacuum forming was easier when applied to one half of the structure. Temperature control to perform both forming and bonding of the structure simultaneously was difficult. Molding worked especially well for quick prototypes. Photolithographic definition yields flat structures that seal very well at valving regions of the structure but the fabrication process is labor intensive. For high level production, heat staking is the most attractive fabrication method.

## ACTUATION

A number of actuation techniques can be used to apply external pressure to the thin-walled compliant plastic structure to provide valving, pumping, metering and mixing functions. For this work, efforts were concentrated on pneumatic actuation

due to its appeal as a cheap and relatively simple method. Three techniques for accomplishing pneumatic actuation are described. Two are membrane deflection methods and the third used commercially available pneumatic cylinders.

Silicone wafer level actuation was accomplished by etching holes from one side of a wafer down to a 5 μm thick silicon nitride layer on the backside as illustrated in Figure 8a. Sylgard 184 was spun on the wafer at 1000 rpm for 50 seconds subsequently cured at 120°C for 10-15 minutes. The nitride was removed using a dry RIE etch. A second wafer with etched-through holes was bonded to the first wafer such that pneumatic connections were made to the holes using glued-on hose barb fittings. The membranes can be deflected using compressed air. A conventional machining approach to fabricating the same design is to mold silicone buttons then sandwich them between two machined aluminum plates as shown in Figure 8b. A 600 μm thick round membrane 15.7 mm in diameter deflects 3.8 mm at 27 kPa and a 5.1 mm diameter membrane deflected 400 μm at the same pressure. These membranes were typically driven using 300 - 400 kPa air. A clear coverplate was positioned 200 μm away from the membranes prevent them from over extending and to provide an opposed surface against the thin-walled compliant structure could be compressed.

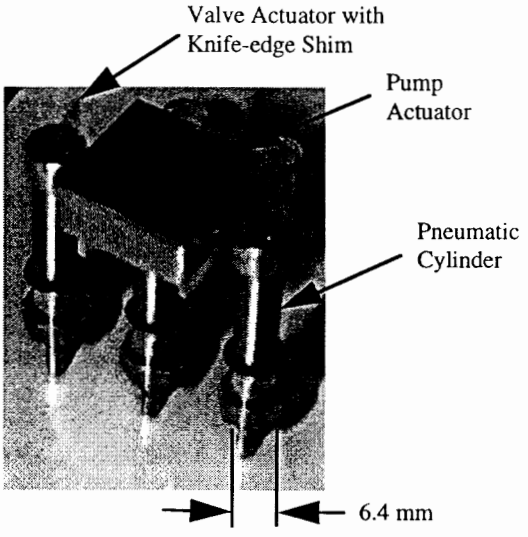


Figure 9. Actuation using pneumatic cylinders.

A disadvantage of the membrane actuation approach is that the actuator deflection is not the same for two different size membranes at a given pressure. Since the plastic insert was placed at a fixed distance from the actuation plate, larger membranes used for pumping were overinflated compared to the smaller membrane actuators used for valving. In addition, the desired operating pressure of valves was greater than for pumps in order that sufficient force be applied to valve regions of the plastic structure to ensure good sealing. An alternative to pneumatic membrane actuators is to use small pneumatic cylinders terminated by plates which apply force to specific locations on the thin-walled, compliant plastic structure. In Figure 9 are shown two valving actuators and a pump actuator built using 6.4 mm diameter Clippard pneumatic cylinders. Flat 6.4 mm thick aluminum plates were attached to the pneumatic cylinders and were used to provide pumping. Grooved plates with a 250 μm polycarbonate knife edge were used to increase the pressure applied to the thin-walled tube in areas used for valving. We used 400 kPa pressure on these devices which were capable of sealing 180 μm gaps in silicone molded valve areas to at least our standard operating pressures of 50 kPa.

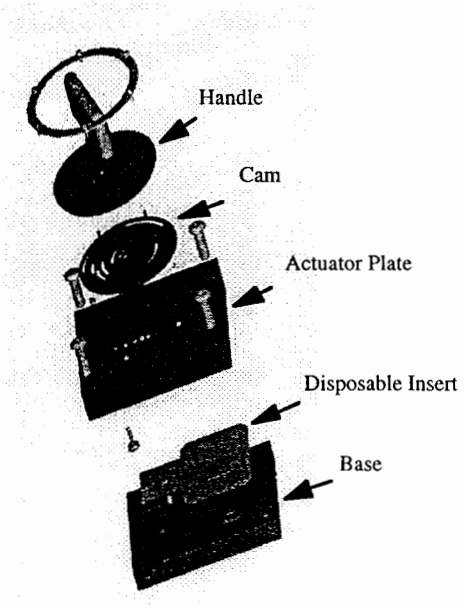


Figure 10. Handheld cam device for manipulation of fluids in plastic structures for field-portable analysis.

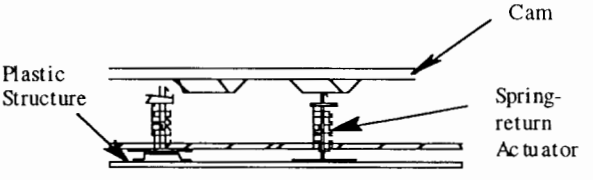


Figure 11. Manual method for low-power actuation.

The use of pneumatic actuators is attractive for many automatic laboratory-based fluidic systems because of the ability to generate relatively high force over relatively large actuation distance for compact microfluidic circuits. However, the use of pneumatic actuators is unattractive for field-portable units since their use requires heavy, bulky, power intensive equipment such as a gas source, pneumatic valves, a power supply for the valves and a controller. These additional external components were eliminated through the use of the manual mechanical cam system built for field portable applications shown in Figure 10. The thin-walled, compliant plastic structure was placed between a manual actuation plate and a base. Spring loaded actuators such as those shown in Figure 11 are forced against the thin-walled plastic structure at specified times during a sample preparation protocol according to ridges of the cam which is turned manually. Fluids were moved through the plastic structure using the pumping and valving techniques discussed previously in this paper to provide for a low-power portable biological or chemical sample preparation module.

## CONCLUSION

The use and manufacture of microfluidic systems based on flexible, thin-walled, compliant plastic structures for meso-scale fluidic systems was discussed. These structures have advantages over rigid walled systems in terms of decreased cost and fewer chemical compatibility issues for use in biological and chemical assays. Completely monolithic plastic fluidic structures were manufactured inexpensively and inserted into a larger system which provided the external actuation for manipulation of the fluid within the plastic structure. Valving, pumping, mixing and metering of fluids to an accuracy of ±5% was demonstrated. Various methods for fabrication of the thin-walled structures were discussed including laser welding, molding, vacuum forming, photolithographic definition and heat staking of polypropylene, polyethylene, silicone and metallocene structures. Laser welding, molding and photolithographic techniques can easily accommodate design changes, but thermal heat staking is the least expensive method for manufacturing large quantities of thin-walled plastic structures. Pneumatic actuation methods which are completely isolated from the working fluid within the thin-walled plastic structure were discussed. These include membrane methods and actuators built using pneumatic cylinders. Membrane methods are compact and are compatible with wafer-level system integration. Pneumatic cylinders can be used to provide greater actuation displacement versus a membrane actuator. In addition, the actuation force applied to the thin-walled plastic structure can be increased by decreasing the actuator contact area for the same actuation pressure. A low-power, manual, cam-driven, spring-loaded actuator system for a field-portable sample preparation module was introduced. This unit does not require ancillary actuation equipment such as air and power supplies.

## ACKNOWLEDGMENTS

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